Impact of the antenna orientation for distance estimation

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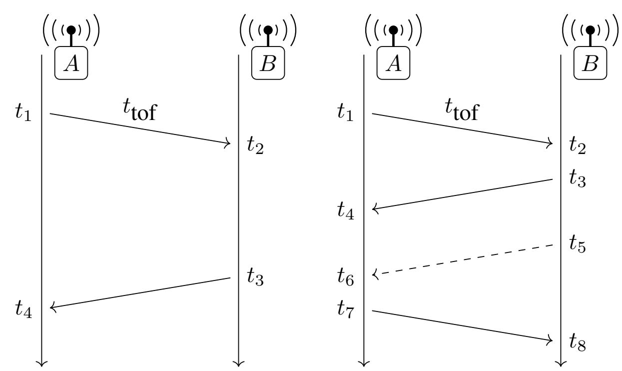
***Abstract*—Indoor localization is important for a wide range of use cases including industrial, medical and scientific applications. The location accuracy is affected by the localization algorithm and the quality of the measurements as input for the algorithm. Many indoor localization systems employ ultra-wideband distance measurements, as they offer high accuracy and are cost effective. One of the methods for distance measurement is two-way ranging. This paper investigates the impact of the antenna orientation on the distance measurement based on symmetrical double-sided two-way ranging. We show that up to 0.25 m of the measurement error is attributed to the orientation of the antennas. We provide explanations and suggest solutions to reduce the effect.**

***Index Terms*—signal strength range-bias, antenna orientation, two-way ranging.**



(a) TWR. (b) SDS-TWR.

Fig. 1: Message exchange diagram of two-way ranging (TWR) and symmetrical double-sided two-way ranging (SDS-TWR)
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I. Introduction

Precise indoor localization is important for a wide range of applications, including safety-relevant real-time localization. Such systems monitor the location of persons continuously. When a person is located in the proximity of a machinery, the person is warned and eventually, the machinery is stopped. Additional, in emergency situations, save and rescue personnel finds remaining persons more easily with the known location.

Many indoor localization systems employ ultra-wideband distance measurements. Consequentially, accuracy and precision of the distance measurement are crucial for the location estimation. In general, the location error is in the same order of magnitude than the error of the distance measurement, if no additional filtering is applied as shown in the Cramer-Rao lower bound [1] or simulations e.g. [2].

In previous work, we investigated different methods for distance measurements based on plain *two-way ranging*. All distance measurement methods achieve similar results in terms of accuracy and precision. The basic method for two-way ranging is shown in Fig. 1a.

Node A and B exchange messages and calculate the time-of-flight as $t_{\text{tof}} = (t_4 - t_1) - (t_3 - t_2)$. By multiplying the time-of-flight with the propagation speed of the radio wave (namely the speed of light), we calculate the distance between A and B. The variant symmetrical double-sided two-way ranging compensates the clock drift between A and B. However, [3] showed, that with commercial-off-the-shelf hardware, the clock drift is negligible as long as the crystal deviations are below 5 ppm. In that case, all variants of distance measurement methods deliver similar performance in terms of accuracy and precision.

The evaluation [3] was carried out under lab conditions, meaning sender and receiver are carefully aligned, to avoid an additional source of error. The alignment of the nodes in Fig. 1a is important as it affects the received signal strength that is correlated to the range-bias [4]. As the antenna gain changes with the orientation, caused by the radiation pattern, this affects the distance measurement.

In this paper, we investigate whether the orientation has an impact on distance measurements and determine the magnitude of this error. A similar investigation was carried out by Ledergerber and D'Andrea in [5]. However, the focus of Ledergerber and D'Andreas work was to model the measurement error rather delivering an explanation.

The rest of the paper is structured as follows: Sec. II presents our measurement setup and Sec. III shows our result. We present explanations for this behavior as well as a solution in Sec. IV and conclude our paper in Sec. V.

II. Measurement Setup

We use the following measurement setup shown in Fig. 2. We place five reference points (white nodes) that are devices

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with known location and orientation, at the corner of the target area. The orientation is the preferred direction of the radiation pattern of our antenna. We place the tag (black node) at each grid point and measure the distances to each reference point. For each measurement, we rotate the tag clockwise in 90° steps. For each point of the grid, we collect 750 measurements. The grid points are 1 m apart, resulting in 20 test points with a total of 60 000 measurements covering 5×4 m.

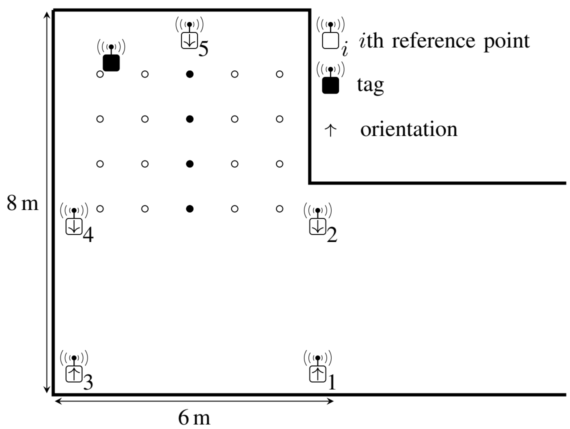

Fig. 2: Measurement setup in our floor.

As the location is known, we calculate the difference μ between the measured distance $\hat{d}$ and the true distance d. In addition to the distance, we record the received signal strength of the first path of the exchanged messages [6].

The hardware for this setup is based on the IEEE 802.15.4a compliant radio unit DWM1000 from Decawave, providing precise timestamping. We perform symmetrical-double-sided two-way ranging, cf. Fig. 1b to measure the distance between the tag and reference points.

III. Evaluation

The empirical cumulative distribution function (CDF) of the measurement error μ (including all orientations and all reference points) is shown in Fig. 3. The mean error is 0.54 m, the median error is 0.47 m, the standard deviation is 0.60 m and the interquartile range (IQR) is 0.30 m. Those measurements values are worse compared to our previously collected measurements in [3], where we derived a mean distance error below 0.10 m. Please mind, that the range bias is not compensated and we only report the raw, unfiltered distance measurements. The mean and median received signal strength is -86 dB, the standard deviation is 3.5 dB and the IQR is 1.8 dB, indicating very stable power measurements.

Next, we choose the 5th reference point and investigate in detail the impact of the orientation to the result. Note, that the remaining reference points show a similar behavior and this discussion is only exemplary. The 5th reference point faces down, according to Fig. 2 and the orientation change is mainly induced due to the rotation of the tag and not when the tags move along the grid. We show the box plots of the measurement error μ in Fig. 4.

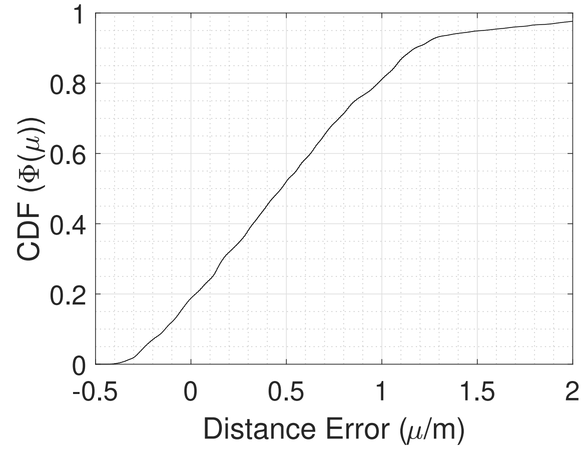

Fig. 3: Empirical cumulative distribution function of the measurement error μ.

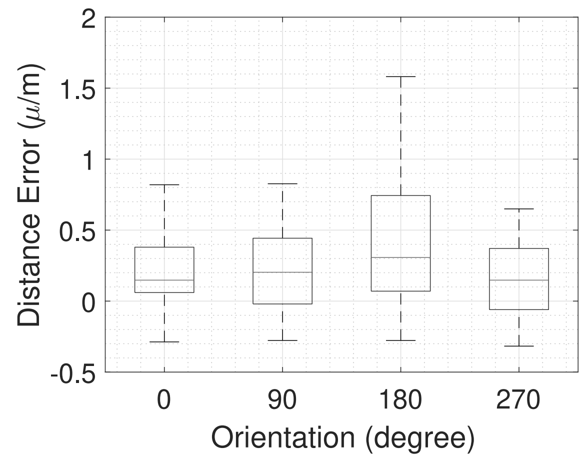

Fig. 4: Boxplot of the measurement error μ for the 5th reference point for all grid points.

The box represents the interquartile range (IQR), which are calculated by the difference of the 75th and the 25th percentile. The central mark indicates the median of the measurement errors. The data enclosed in the whiskers have a length of $1.5\times$ the IQR. In this data set, no outliers are present.

If the orientation does not matter, we would expect that the statistical parameters of each box plot are similar, however, we notice a difference at each investigated orientation. We report the numerical values of the mean, median, standard deviation and IQR in Tab. I. We also report the measured received signal strength for each orientation in Tab. I. Based on symmetry considerations, we expected the 90° and 270° to be equal — which proofed wrong. The relative error, which is the difference between the minimum (i.e. 0.16 m) and the maximum (i.e. 0.41 m), is for the mean 0.25 m and for the median 0.16 m. This error is directly induced due to the orientation change. We also note, that the received signal strength does not change with the orientation and is almost constant. In the last evaluation, we evaluate the grid points below the 5th reference point, those are

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TABLE I: Performance metrics for the 5th reference point for all orientations and grid points.

orientation [°]	0	90	180	270
mean error [m]	0.21	0.23	0.41	0.16
median error [m]	0.15	0.20	0.31	0.15
standard deviation [m]	0.26	0.29	0.39	0.25
IQR [m]	0.32	0.46	0.67	0.43
mean RSSI [dBm]	-85.5	-86.0	-87.0	-85.5
median RSSI [dBm]	-85.5	-85.8	-86.2	-85.4
std RSSI [dB]	3.67	2.69	2.89	3.00
IQR RSSI [dB]	0.96	1.02	2.09	0.91

indicated as filled black dots. In this case, the only parameter we vary is the distance towards the 5th reference point and the orientation of the tag. We report the data in Tab. II. In this case, the orientation is affecting the measurement error, particular at a orientation of 90 ° and 180 ° The maximum relative error for the mean is 0.12 m and 0.10 m for the median. The received signal strength again is almost constant, similar to Tab. I. Our findings support the measurement of Ledergerber and D'Andrea [5].

TABLE II: Performance metrics for the 5th reference point for all orientations. Only the filled black dots are evaluated.

orientation [°]	0	90	180	270
mean error [m]	0.09	0.15	0.21	0.09
median error [m]	0.13	0.19	0.23	0.13
standard deviation [m]	0.08	0.09	0.12	0.10
IQR 90 [m]	0.10	0.15	0.24	0.17
mean RSSI [dBm]	-85.1	-86.0	-85.7	-85.2
median RSSI [dBm]	-85.2	-86.0	-85.8	-85.2
std RSSI [dB]	3.25	2.45	2.36	2.33
IQR RSSI [dB]	0.66	1.40	0.80	0.72

IV. Discussion the findings

At a first glance, the signal strength range bias is a reasonable explanation for the behavior. This range bias of the DW1000 is not directly affected by the distance of the reference point and the tag but depends on the received power, which, in return, depends on the distance to each other [4].

If the range bias is the sole explanation for the phenomena, we expect a symmetry in Tab. II, particularly at a orientation of 90 ° and 270 °. The received signal strength reported in Tab. I did not support this hypothesis. The antenna of the DWM1000 is the ACA-107-T from Abracon. The data sheet from Abracon indicates an almost omnidirectional radiation pattern [7]. Based on the data sheet, the antenna gain due to the orientation is about 10 dB for a frequency of 6.2 GHz. This corresponds to the measured received signal strength variation.

The maximum magnitude of the distance estimation error is between 0.16 m up to 0.41 m, according to Tab. II and Tab. I. The relative error is 0.25 m and caused by the orientation. In contrast, an error of 0.15 m caused by the range bias requires the received signal strength to change by 25 dB, which is not explained by the radiation pattern of the antenna and not supported by the received signal strength measurements [4]. Therefore, we conclude that the range bias is not the explanation of this phenomenon.

An alternative explanation that changing of the orientation affects the rf-propagation path. This results in another accumulated channel impulse response, which is in return evaluated by the DWM1000 to estimate the exact receive time stamp, cf. Fig. 1a and Fig. 1b. This would not directly impact the received signal strength, but only the timestamp.

One possible solution towards this problem includes the incorporation of multiple antennas. Kempke et al. suggested such a solution in [8]. However, one of the main aspects of the DWM1000 is its off-the-shelf availability. Such modifications increase costs, however, for testing of the solution, usage of multiple DWM1000 may prove useful.

V. Conclusion and Future Work

In this paper, we investigated the impact of the orientation towards the distance measurement using symmetrical double-sided two-way ranging. We found that the orientation has an impact towards the distance measurement. In our investigation, the change of the orientation of a tag, caused the distance measurement to change by up to 25 cm. We investigated, whether the signal strength range bias is responsible for this measurement error. Our analysis of the evaluation results shows that this source of error does not explain the measurement error.

We assume that the orientation changes the rf-propagation path and thus influence the distance measurement. To validate this claim we propose to use multiple antennas to investigate this behavior in more detail.

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